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Research Article

Heat Exchange of Marine Tankers' Tubular Heater

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Abstract

The investigation of the heat exchange of the marine tankers' tubular heater made it possible to receive criterion equations for calculating average and local heat emission in free convection for a wide range of Ra and Pr numbers taking into account the variable viscosity. The oscillations intensify the heat exchange process. The heat exchange process of tubular heater while tankers are tossing belongs to a stationary mixed convection. Three zones of oscillation influence on the heat exchange of the horizontal cylinder are formed, and the boundaries of these zones are determined. The criterion equation, which generalizes the heat exchange at vibration, oscillations, rotation and horizontal cylinder flow, is received.

Keywords: *heat exchange, variable viscosity, oscillations, horizontal cylinder, tossing, marine tankers.*

Introduction

For heating viscous liquids during transportation on tankers, steam coiled or sectional tubular heaters are mainly used. Parameters of a heater (heat transfer surface, effective length of a heater, hydraulic resistance, etc.) significantly depend on the intensity of the heat exchange between the heat fluid and the outer surface of the pipes of a heater. On marine tankers rolling influences significantly on the heat transfer of a heater [Sherbakov A.Z., Selivanov N.V., Belonogov V.A.1983]. Inaccurate determination of heat transfer coefficient between the fluid and the surface of a heater will increase capital and operating costs for the heating system for liquid cargo and will ultimately increase the cost of viscous oil transportation. That is why the study of the influence of capacity fluctuations on the heat transfer around a horizontal tubular heater is one of the most urgent tasks for transportation of high-viscosity liquids by sea.

The influence of the vibration in a horizontal cylinder on the heat transfer during the free convection process is considered in [Galiceiskiy B.M., Rigov U.A., Yakush E.V. 1977 - Richardson P. D., Tinactin K.1974], the most work is focused on low-amplitude high-frequency oscillations (vibrations). In the area of low relative amplitudes the movement of the fluid around the cylinder is aperiodical. There is a critical level of the vibration intensity below which the heat transfer is not very different from the free convection process. By increasing the relative amplitude of $A/d > 0.25$, according to [Carr W., Black W. Z 1974.], the critical level is not observed, and the heat transfer gradually increases with increasing of the amplitude and the frequency of vibration. For the area of relatively large amplitudes the heat transfer process can be considered as quasi-stationary [[Galiceiskiy B.M., Rigov U.A., Yakush E.V. 1977, Carr W., Black W. Z.1974, Diver F.K., Penney V.R., Jefferson T.V.1962]. The heat transfer during the vibration with large-amplitudes is approaching, in a sense, the heat transfer during the cross flow of the cylinder. With increase of the oscillation frequency of the cylinder mainly small-scale and turbulent disturbances occur. Since high-frequency pulsations in the fluid decay rapidly without extending to the volume, this leads to the slowdown of the growth rate of the heat transfer [Kremnev O.A., Satanovskiy A.V., Lopatin V.V.1968].

To assess the impact of the fluctuations on the heat transfer of the horizontal cylinder it is necessary to know the intensity of the heat transfer during the free convection process. Analysis of the results obtained in [Akagi S. 1965, Kuehn T. H., Goldstein R. J. 1980] has shown that at $Ra \leq 10^5$ the approximations of the boundary layer are invalid. For this case, the dependence for calculation of local heat transfer coefficient, which approximates the results of the numerical solutions [Akagi S. 1965 – Selivanov N.V.2002] at $Ra \geq 10^2$ with an accuracy of 2% in the range of variation $Pr_l = 0.01 - \infty$ has been obtained:

$$Nu_{d,l} = Ra_{d,l}^{0.25}\left[\left(\frac{Pr_l}{1+2\left(Pr_l^{0.5}+Pr_l\right)}\right)^{0.25} g(\varphi)(\bar{\mu})^k + \frac{1{,}2{Pr_g}^{0.0147}}{Ra_{d,l}^{0.25}}\right] \qquad (1)$$

where $Nu_{d,l} = \alpha d/\lambda$ – the Nusselt number; $Pr_l = \nu/a$ – the Prandtl number; $Ra_{d,l} = g\beta\Delta t d^3/(\nu a)$ – the Rayleigh number; $\mu = \mu_l/\mu_w$ – relative viscosity (μ_l and μ_w – dynamic viscosity at the liquid temperature and the wall temperature respectively, Pa·s); α – heat transfer coefficient W/(m²·K ·); λ – thermal conduction coefficient, W/(m·K); ν – kinematic viscosity of the liquid, m²/sec; β – temperature coefficient of the thermal expansion of the

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fluid, 1/K; a – thermal diffusivity coefficient, m^2/s; d – diameter of the cylinder, m; $\Delta t = t_w - t_l$ – the temperature difference between the surface of a heater and the fluid, K.

The value of $g(\varphi)$ can be approximated by a polynomial to perform engineering calculations $g(\varphi) = 0.76 - 0.348(\frac{\varphi}{\pi})^2 - 0.155(\frac{\varphi}{\pi})^4$, k = 0.17 at $t_w < t_l$ and k = 0.21 at $t_w > t_l$.

Comparison of the calculated dependence (1) with the experimental data [Kuehn T. H., Goldstein R. J. 1976, Brdlik P.M.1983] and the obtained data calculated in a wide range of Prandtl numbers has shown that the equation (1) fairly well summarizes the experimental data (figure 1, a).

To calculate the average heat transfer of the horizontal cylinder during the free convection processs, we recommend the dependency which generalizes the theoretical solutions taking into account the variable fluid viscosity [Selivanov N.V. 2002] and the experimental data about the heat transfer at $Ra \geq 10^5$ (figure 1, b) in a wide range of Prandtl numbers with an error of ± 2%:

$$Nu_{d,l} = 0.619 Ra_{d,l}^{0.25} \left[\frac{Pr_l}{1+2(Pr_l^{0.5}+Pr_l)}\right]^{0.25} \bar{\mu}^{0.21} \quad (2)$$

Due to the absence of any research about the influence of capacity fluctuations on the heat transfer of the horizontal cylinder, an experimental research has been carried out.

Experimental research

The experiments have been carried out using a device, which is a prismatic tank with internal dimensions 1.0×1.5×0.5 m producing harmonically oscillations around a horizontal axis. The transparent front walls allowed to carry visual observations of the flow hydrodynamic processes of the horizontal cylinder. The liquid level in the tank varied from 0.5 to 1.5 m, and the relative width of the tank was from 0.67 to 2.0. As a working fluid medical vaseline oil has been used. To examine the impact of capacity fluctuations on the heat transfer of the horizontal cylinder, cylindrical heaters with dimensions 60×4 , 12,5×2 mm have been used. The local temperature of the heater's surface has been measured by copper constantan thermocouples. Electromotive force of the thermocouples has been measured by a potentiometer R368 (accuracy class 0.02); the electrical power of the heater – by UMK K565 (accuracy class 0.5). During the experiments, the angular amplitude Θ_0 varied from 2 to 16.5º, the period T = 2-16 sec, the liquid temperature t_l = 20-50 ºC, the temperature of the heater's wall t_w = 50-150 ºC; the heat flux was 0,70-20,0 kW/m^2. A maximum error of the temperature calculations was ± 1 ºC. An error of determining the temperature does not exceed ± 2%; the heat transfer coefficient at the surface of the heater was ± 5%.

Discussions about the results

The experiments with absence of capacity fluctuations have provided the possibility to take the values of local and average heat transfer coefficients of the horizontal cylinder during the free convection process. The experimental data is in good agreement with the numerical solutions and dependencies (1) and (2), which confirm the reliability of the chosen method of research (figure 1).

Visual observations have shown that for small values of amplitude fluctuations and for large periods the impact of the periodic motion of the fluid is relatively small and leads to the shift of the area, where a trace appears over the top surface of the heater, and the trace takes the form of a sine wave, decaying throughout the height (figure 2, a). For large values of the amplitude and low values of the oscillation period the fluid motion caused by capacity fluctuations is dominant and the "trace" from the heater is transported by secondary flows and it leads to the intensive mixing of hot and cold liquid mass (figure 2 b, c).

The influence of the relative amplitude (A/d), and the mutual influence of the heaters on the heat transfer within the specified range of their alteration have not been found out, which coincides with the results [Kremnev O.A.,1968, Carr W., Black W. Z.1974, Diver F.K., Penney V.R., Jefferson T.V.1962]. The influence of the geometry of the cavity on the heat transfer rate is taken into account adequately when the Re number is calculated according to the velocity of the fluid towards the cylinder: $Re = 2\pi\Theta_0' h' d/(T\nu)$, where $\Theta_0' = \Theta_0 f(b/h)$ – angular amplitude of liquid oscillations.

The value $f(b/h)$ according to [Selivanov N.V.2000] can be determined from the equation:

$$f(b/h) = 1.713(b/h) - 0.3164(b/h)^2 - 0.037(b/h)^3 \quad (3)$$

Analysis of the results has shown that with increasing of $Re_{d,l}$, and reducing of $Ra_{d,l}$, the intensifying effect of the forced movement of the liquid caused by capacity fluctuations increases, and the impact of the free convection process on the heat transfer reduces and then disappears. With the increasing value of the Prandtl number this influence increases and shifts to the area with lower values of the Reynolds number. The intensity of the heat transfer during capacity fluctuations increases 1.5-4 times compared to the free convection process.

The presence of three zones of the heat transfer depending on the intensity of vibrations has been observed, the boundaries of the zones depend on the complex $Re^{2,4}/Gr$ and the Prandtl number:

- a zone of the dominant influence of the free convection process;
- a zone of the mixed convection where fluctuations have an intensifying impact on the heat exchange;
- a zone of the dominant influence of forced movements caused by capacity fluctuations.

The experimental data under the dominant influence of forced movements caused by capacity fluctuations are summarized with an accuracy of ± 5% by the following equation:

$$Nu_{f,d} = 0.272 Re_{d,l}^{0.6} Pr_l^{0.38} \bar{\mu}^{0.275} \quad (4)$$

The equation (3) is valid in the following range of the dimensionless variables: $Re_{d,l}$ = 5 – 350; Pr_l = 500-2000; b/h = 0.67-2.0; $Gr_{d,l} \leq 6{\cdot}10^5$; $Gr/Re^{2,4} \leq 1$. The impact of variable liquid viscosity on the heat transfer is taken according to [Selivanov N.V.2002]. The structure of the dependence (3) coincides with the equation of the heat transfer under the forced convection process around the cylinder and is almost identical to the results of [Kremnev O.A.,1968].

In the area of the mutual influence of the free and forced convection processes caused by capacity fluctuations it is necessary to take into account their combined contribution to the heat transfer.

For the mixed convection process, the equation for the heat transfer according to [Selivanov N.V.2000] is following:

$$Nu_{mc} = \left(Nu_{fc}^4 + Nu_f^4\right)^{1/4} \quad (5)$$

where Nu_{mc}, Nu_{fc}, Nu_f – the Nusselt number under the mixed convection process, the free convection process and fluctuations respectively.

Taking into account the equations (2) and (3), the equation (4) for the average heat transfer under capacity fluctuations for $Pr_l \geq 100$ can be transformed into:

$$\frac{Nu_{mc}}{Nu_{fc}} = \left[1 + 0.081 \frac{Re_{d,l}^{2,4}}{Gr_{d,l}} Pr_l^{0.52} \bar{\mu}^{0.26}\right]^{1/4} \quad (6)$$

The results of the comparison of the experimental data about the heat exchange with the calculation according to the equation (5) are shown in figure 3, a. Figure 3, a shows that the agreement between the calculated (5) and the experimental data is quite good and therefore the equations (4) and (5) can be recommended to calculate the average heat output of the horizontal cylinder with capacity fluctuations.

The relation (5) allows to define the boundaries of the mixed convection area, where the influence of one of the convections can be neglected with an error of no more than 2 %.

Thus, for liquids under the mixed convective complex with $Pr_l \geq 10$ at $B = Re_{d,l}{}^{2,4} \frac{Pr_l{}^{0.52}}{Gr_{d,l}} \leq 1.0$ the influence of the forced convection on the heat transfer can be neglected, and the heat transfer is determined only by the free convection process around the horizontal cylindrical heater and is calculated using the formula (2).

For B ≥ 125 the influence of the free convection process on the heat transfer can be neglected and heat transfer coefficient is calculated using the relation (3).

In the area of change B from 1.0 to 125 the heat exchange process is determined by the combined action of the free and forced convection processes caused by capacity fluctuations, so heat exchange coefficient ought to be calculated using the equation (4).

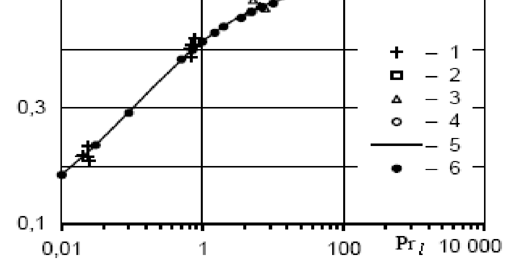
Figure 3b shows the results of the comparison of the experimental data about the heat transfer around the horizontal cylinder under its fluctuations, vibrations and rotation. The comparison shows that the dependence (4) summarizes the experimental data about the heat transfer under vibrations and rotation of the horizontal cylinder in the air and in high viscosity liquids [Kremnev O.A., Satanovskiy A.V., Lopatin V.V.1968, Buznik V.M., Vezlomcev K.A.1961, Richardson P. D., Tinactin K.1974].

Conclusions

Thus, the heat transfer around the horizontal cylinder under vibrations and capacity fluctuations in a tank, where the heater is arranged, can be determined as the heat exchange under the process of stationary mixed convection.

The results of the research allow:

- to identify three areas of the impact of fluctuations on the heat transfer, where the influence of one of the convection types can be neglected. The boundaries of these areas depend not only on the mixed convection parameter, but also on the Prandtl number. With increasing of the Prandtl number, the impact of fluctuations on the heat transfer increases;
- to establish that capacity fluctuations intensify the heat transfer around the horizontal cylinder 1.5-4 times compared to the free convection process;
- to get calculation dependences for the average heat transfer around the horizontal cylinder in the whole range of the mixed convection processes taking into account variable physical properties of the liquid;
- to recommend the dependence (4) taking into account the equations (2) and (3) to calculate the heat transfer around horizontal tubular heaters within heating systems for liquid cargo on tankers under the rolling conditions and under vibrations of the horizontal cylinder.



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The results allow to improve the reliability and efficiency of tubular heating systems on oil tankers, and can also be used to intensify the heat transfer processes around the horizontal cylinder in devices of the chemical and petrochemical industries.

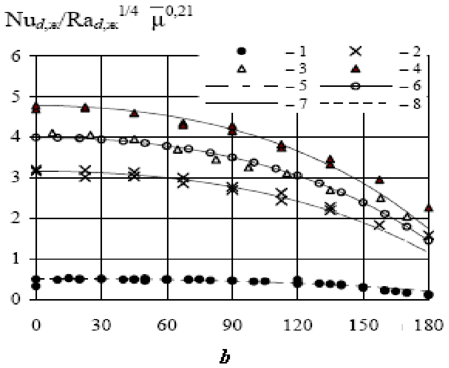


Fig. 1. Heat transfer around the horizontal cylinder under the free conduction process: a – the local heat transfer: 1 – Pr = 0.72 [Kuehn T. H., Goldstein R. J.1976]; 2 – 530; 3 – 1340 [Brdlik P.M.1983]; 4 – 2700; the calculations according to (1): 5 – Pr = 530; b – 1340; 7 – 2700; 8 – 0.72; b – the average heat transfer: 1 – [Hessami M.A., Pollard R.D., Raw R.D.1985]; 2 – [Acagi S.1969]; 3 – obtained; 4 – [Selivanov N.V.2000]; 5 – the calculations according to (2); b – the numerical solution [Selivanov N.V.2002].

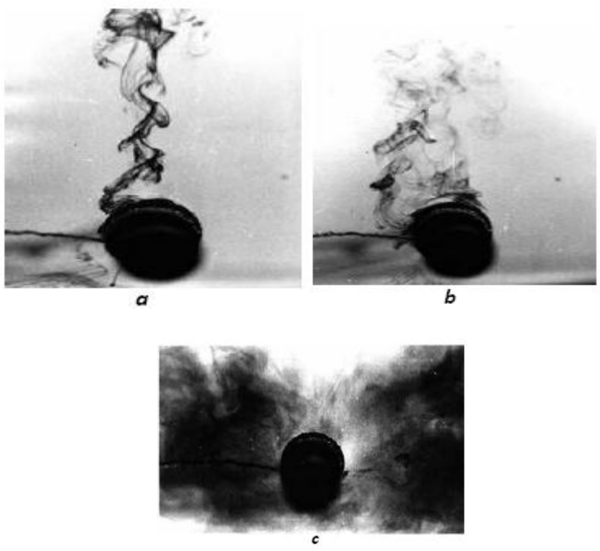
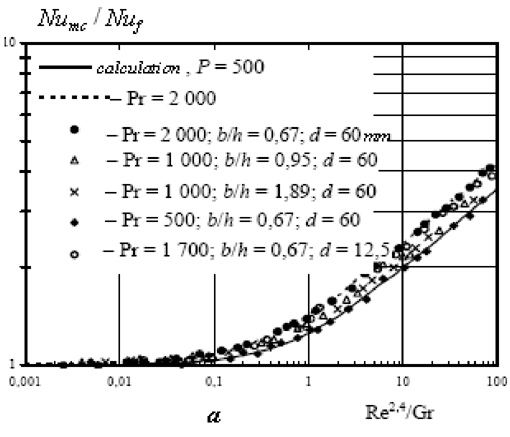


Fig.2. Flow pattern around the horizontal cylinder: a – during small; b – during medium; c- during intensive capacity fluctuations.



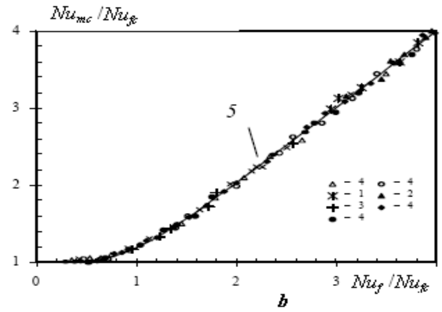


Fig. 3. Heat transfer around the horizontal cylinder under fluctuations: a – comparison of the experimental data with the calculations using the equation (5); b – generalization of the experimental data under the fluctuations and rotation of the cylinder; 1 – oil [Kremnev O.A., Satanovskiy A.V., Lopatin V.V 1968]; 2 – Pr = 0.72, rotation and vibrations [Buznik V.M., Vezlomcev K.A.1961]; 3 – Pr = 0.72, vibrations [Richardson P. D., Tinactin K. 1974]; 4 – the same as on figure 3, a; 5 – calculation using the equation (4).

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